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ADVANCED CAPACITATIVE OIL DEBRIS MONITOR

Richard H. Hollinger

Franklin Institute Research Laboratories

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13. ABSTRACT

The object of this program was to design, build, and calibrate two models of an advanced capacitative oil debris monitor based on the principle and design of a prototype monitor developed under Contract DAAJ02-71-C-0018. Two models were provided: one to cover an oil flow range up to 3 gallons per minute, and a second to cover the oil flow range of 3 gallons per minute to 12 gallons per minute. The report includes installation and operation instructions.

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DEPARTMENT OF THE ARMY
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EUSTIS DIRECTORATE
FORT EUSTIS, VIRGINIA 23604

This report was prepared by Franklin Institute Research Laboratories under the terms of Contract DAAJ02-72-C-0078. It presents a description of a 9-month effort to design, build, and calibrate two models of an advanced capacitative oil debris monitor based on the principle and design of a prototype model developed under Contract DAAJ02-71-C-0018. These models will provide continuous in-line oil debris monitoring capabilities that will further enhance diagnostic/prognostic efforts.

The design was modified to compensate for temperature effects and to be adaptable for use on UH-1 helicopter components. One unit is to be used on a UH-1 transmission; the second unit is to be used on a modified UH-1 90-degree gearbox.

The conclusions and recommendations contained herein are concurred in by this Directorate. Both units have been successfully modified and fabricated, and the 90-degree gearbox model is undergoing tests.

Technical direction for this contractual effort was provided by Messrs. Meyer B. Salomonsky and Roger J. Hunthausen.

Task 1F162205A11908
Contract DAAJ02-72-C-0078
USAAMRDL Technical Report 73-53
August 1973

ADVANCED CAPACITATIVE OIL DEBRIS MONITOR

Final Report

by

Richard H. Hollinger

Prepared by

Franklin Institute Research Laboratories
Philadelphia, Pennsylvania

for

EUSTIS DIRECTORATE
U.S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

SUMMARY

The object of this program was to design, build, and calibrate two models of an advanced capacitative oil debris monitor based on the principle and design of a prototype monitor developed under Contract DAAJ02-71-C-0018. Two models were provided: one to cover an oil flow range up to 3 gallons per minute, and a second to cover the oil flow range of 3 gallons per minute to 12 gallons per minute. The report includes installation and operation instructions.

FOREWORD

This program was carried out for Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory under Contract DAAJ02-72-C-0078, Task 1F162205A11908. The design of the capacitance bridge and servo circuits was conducted by Mr. Ramie Thompson of the Applied Physics Laboratory of the Franklin Institute Research Laboratories. Mr. Meyer Salomonsky of the Eustis Directorate served as Technical Monitor for the program and supplied useful information and encouragement.

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INTRODUCTION

Under Contract DAAJ02-71-C-0018, a prototype device for monitoring the quantity and rate of generation of metallic debris in recirculating lubrication systems was developed and tested. The device was based on the collection of the particulate debris in the annular space between the plates of a cylindrical capacitor. The debris was removed from the oil stream by centrifugal action caused by tangential introduction of the oil flow into the monitor cell, and by passing the flow through a 50-micrometer screen which was continually washed by the fluid flow. The particulate material settled into the measuring capacitor. The fluid which passed through the screen was allowed to flow through a reference capacitor of identical dimensions as the measuring capacitor. By using a bridge circuit with the measuring and the reference capacitors, the effect of oil properties such as temperature and water content could be cancelled, and only the collected metallic debris would affect the bridge output.

The electrical readout system operated by using the bridge unbalance signal as the command signal to drive a servomotor. The motor, in turn, drove a servopotentiometer whose output served both as feedback signal for the motor and display signal for a meter. In practice, an unbalance in the bridge caused the servomotor to drive the servopotentiometer until the feedback signal cancelled the bridge unbalance signal. The unbalance signal was detected at predetermined time intervals; and by comparing the potentiometer signal (which represented the previous reading of metal content) to the new unbalance signal, a reading for difference or rate of generation was determined. A servomotor and servopotentiometer system was used to display the difference signal on a second meter.

The principle of operation of the monitor was proven, but it was found that the bridge unbalance signal was temperature dependent. The dependency was traced to the method of grounding the measurement and reference capacitors, which required alteration of the bridge design. The revised bridge design was to be incorporated into the existing prototype unit and used in a second unit with higher flow capacity.

Two capacitative debris monitors, one for low flow ranges and one for high flow ranges, were built and tested. The monitors were modified to prevent temperature drift effects, and they incorporated automatic timing circuits for sampling interval, as well as output jacks for recording of data.

DESIGN CHANGES

MONITOR CELL

The existing monitor cell had been tested in the previous program at oil flow rates up to 5 gallons per minute. The differential pressure at 5 gpm was found to be 10 psi. The cell would, therefore, be marginal for use at the 12-gpm flow used in the UH-1 lube oil system, and it was decided that the existing cell would be better used for relatively low flow applications such as the UH-1 90-degree-gearbox tests. A second, larger cell was designed for the high flow application.

CAPACITORS

The basic design for the measuring and reference capacitors was retained, but the outer plates of the capacitors were not insulated. This allowed the outer plates to be connected to a common ground using the metal of the monitor housing as a connecting link. The revised grounding method allowed the cells to operate over the temperature range of 75°F to 300°F with only two scale units of drift on the accumulator meters. Thus, on the scale of 0 to 100, a drift of two percent occurs.

READOUT CIRCUIT

The bridge circuit was redesigned to accept the new grounding method for the capacitors, and timing circuits were provided to actuate the measurement and meter circuits at 2-hour intervals. In addition to the readout meters, output jacks were provided for recording the quantity of debris and rate of generation of debris on any high-input-impedance recorder. Each readout unit was reworked to contain its own power supplies, so only 115 Vac, 60 Hz is required for operation.

DEBRIS DETECTOR CIRCUIT

The overall circuitry is shown in Figures 1 through 4. All the operational amplifiers used are Fairchild No. 741. The base diagram for these components is given on Figure 1. To clarify the circuit drawings, the $\pm$ 15 Vdc power supply connections to the operational amplifiers have not been shown.

Basically the circuit must sense the amount of debris in the measurement capacitor, compare this value with the previously determined value, and store the new value for future comparisons. The amount of debris is sensed by comparing the capacities of the reference and measurement capacitors.

Figure 1, the bridge circuit schematic, shows the overall bridge circuit configuration of which the measurement and reference capacitors are a part. The bridge is driven by the 1000-Hz operational amplifier oscillator shown on the left of the figure. The difference in signal values between the points marked SIG. M and SIG. R determines debris accumulation.

Figure 2, amplifier schematics, shows the two operational amplifiers used to isolate the bridge from the following circuitry and the differential operational amplifier that determines the difference between the signals. The 1000-Hz difference signal is rectified and smoothed and then, after amplification by a dc isolation operational amplifier stage, is supplied to the servo loops used to indicate total debris accumulation.

Figure 3, the servo loop schematic, shows the circuitry of the two almost identical servo loops, the switching circuitry used to update the loops, and the differential operational amplifier used to determine the change in accumulation.

Figure 4, the power and control schematic, shows the power supply connections, the timer that determines the update period, and the time delay relays that determine the length and sequence of the updating process.

Circuit operation is most easily explained by following the updating process through a typical sequence. We first assume that the power off/on and the timer off/on switches have been thrown to the "on" position, thus providing dc power to the circuitry and allowing the timed motor to drive. At any time that the dc power is applied to the circuitry and the balanced cables are connected between the measurement head

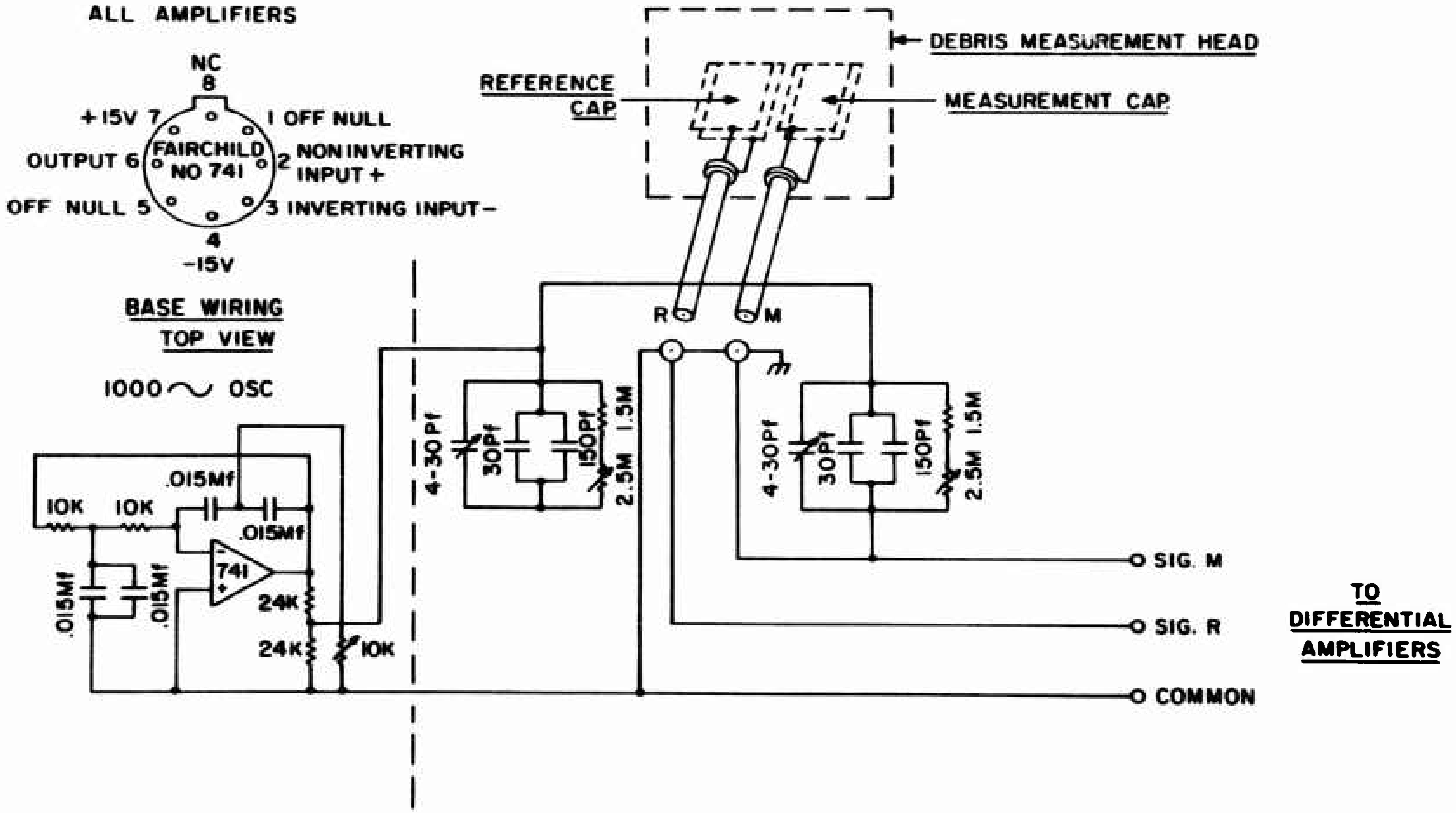

Figure 1. Bridge Circuit Schematic.

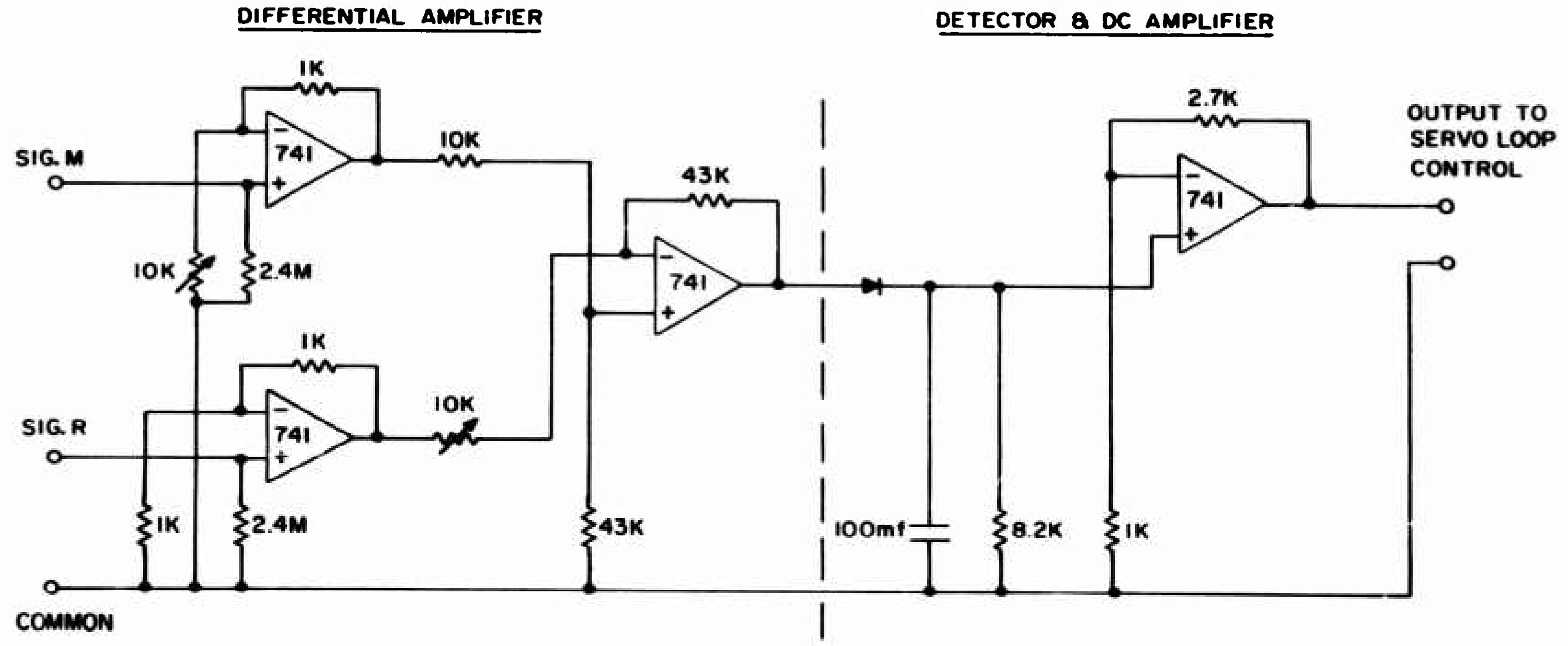

Figure 2. Amplifier Schematics.

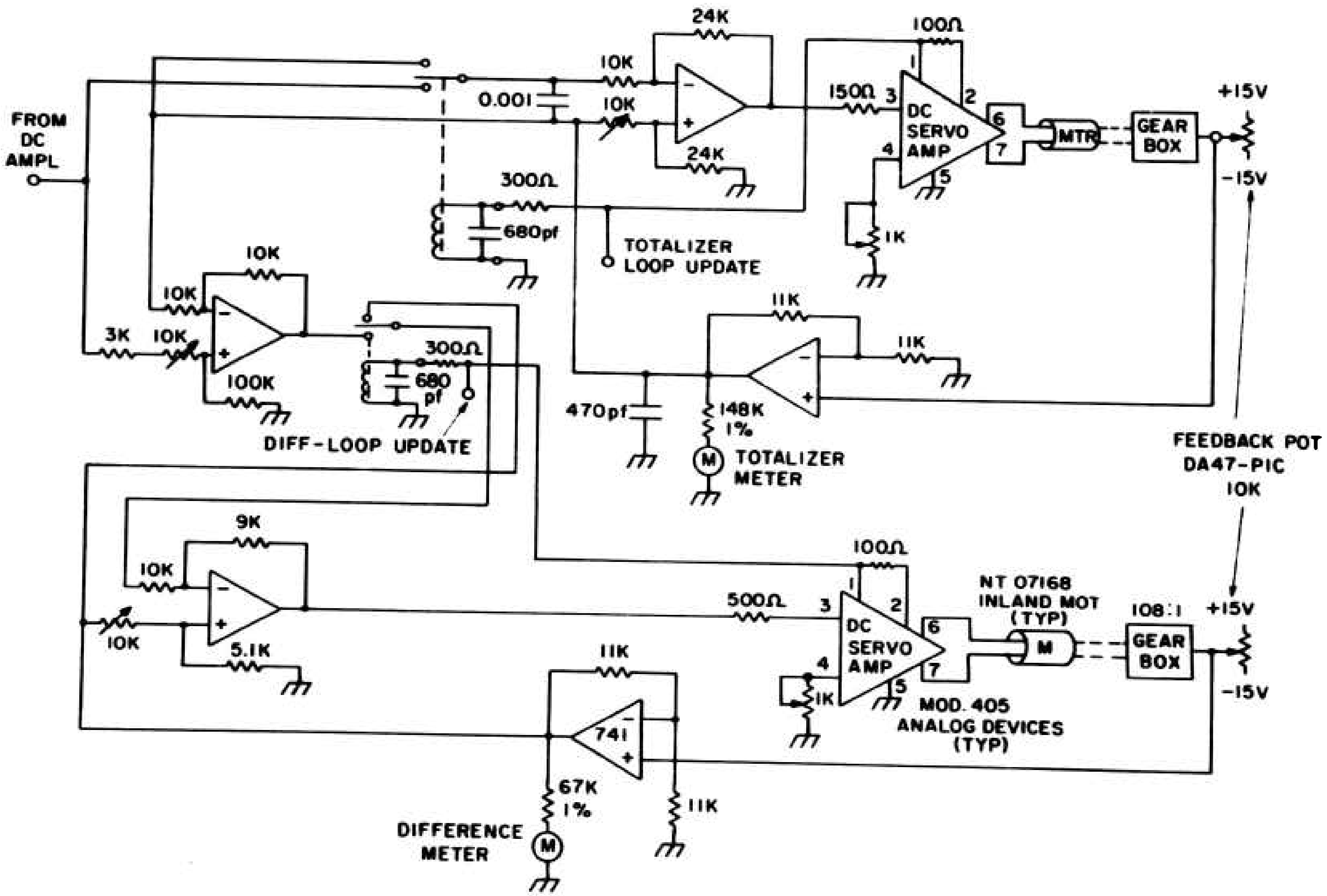

Figure 3. Servo Loop Schematic.

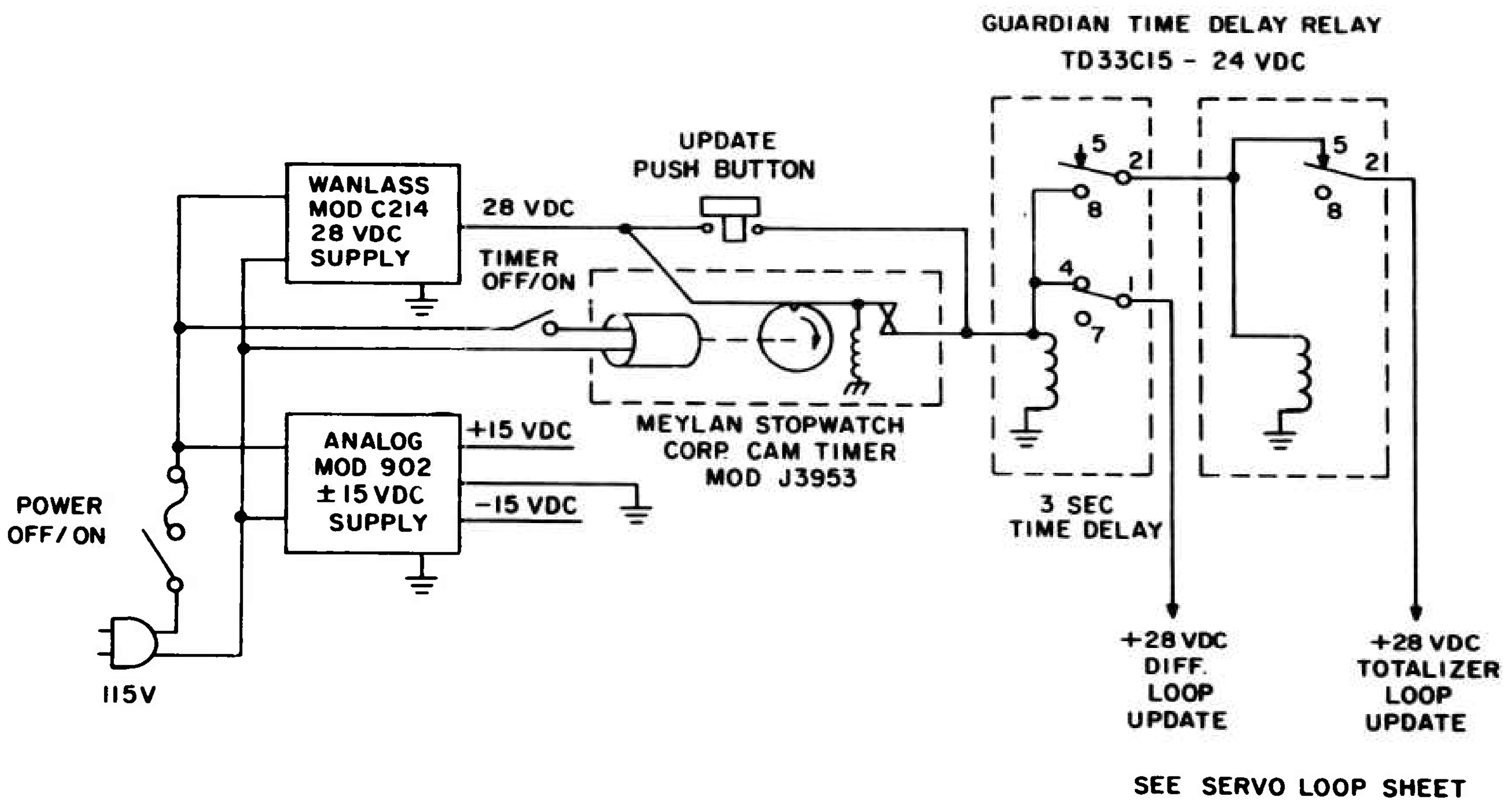

Figure 4. Power and Control Schematic.

and the circuitry unit, the circuitry of Figures 1 and 2 determines the bridge unbalance and supplies a positive dc voltage, which is proportional to the amount of debris accumulation, to the point marked "FROM DC AMPLIFIER" on the left of the servo loop schematic.

The updating process begins with the timing cam of the timer allowing its cam follower to drop into the depression of the cam. The cam is driven by the timer motor at one revolution every 2 hours. The cam follower's travel closes a microswitch that applies 28 Vdc to the first of the time delay relays. The time delay feature of the relay allows its contacts to remain in the position shown for approximately 3 seconds before the relay energizes. During this 3-second interval, 28 Vdc is applied to the point marked "DIFFERENTIAL LOOP UPDATE" on the servo loop schematic. This supplies power to the differential loop servo amplifier and closes the associated signal relay. Note that the differential operational amplifier just to the left of this relay is constantly comparing the present value of debris accumulation with the value held by the total accumulation servo loop. Its output is the difference between the present value and the total accumulation servo loop value. The closing of the control relay supplies this value to the input of the accumulation change or differential servo loop. The servo loop repositions itself to conform with its input, and the difference between the present amount of accumulation and the total accumulation loop value is shown by the "DIFFERENCE METER" in the feedback loop of the servo. At this time the first time delay relay times out and removes voltage from the servo loop and returns the "DIFF-LOOP UPDATE" relay to its original position; the difference meter continues to display the disabled servo loop positions.

When the first time delay relay times out and energizes, it provides 28 Vdc to the second time delay relay. This relay provides, for 3 seconds, 28 Vdc to the "TOTALIZER LOOP UPDATE" point on the servo schematic. This applies 28 Vdc to the total accumulation servo loop servo amplifier and energizes the control relay. The control relay supplies the present value of the amount of debris accumulation to the input of the servo loop. The loop repositions itself to conform to the input and thus displays the present value of accumulation on the "TOTALIZER METER" in the feedback loop. At this time the second time delay relay energizes and disables the loop. A few minutes later the timer cam follower is pushed out of its depression in the cam and the time delay relays deenergize.

At this time the "TOTALIZER METER" reads the present value of debris accumulation and the "DIFFERENCE METER" reads the difference between the present value of accumulation and the value held by the "TOTALIZER METER" before update. The update process is complete and ready to repeat.

The "UPDATE" push button allows checkout of the update process without waiting for the timer to cycle.

DEBRIS SENSOR ASSEMBLIES

LOW FLOW

The sensor assembly for use with flows of 1 gallon per minute is shown in Figure 5. The basic parts of the assembly are:

1. Inlet Port
2. Outlet Port
3. Measurement Capacitor Retainer
4. Measurement Capacitor Assembly
5. 50-Micrometer Filter Screen
6. Sensor Body
7. Sensor Head
8. Collector Groove
9. Connecting Port
10. Reference Capacitor Retainer
11. Reference Capacitor Assembly
12. Location for Control Orifice.

The numbers above correspond to those in Figure 5.

HIGH FLOW

The sensor assembly for use with flows from 6 to 13 gpm is shown in Figure 6. Except for size, the basic design is essentially the same as for the low-flow sensor, but the sensor head has been modified to

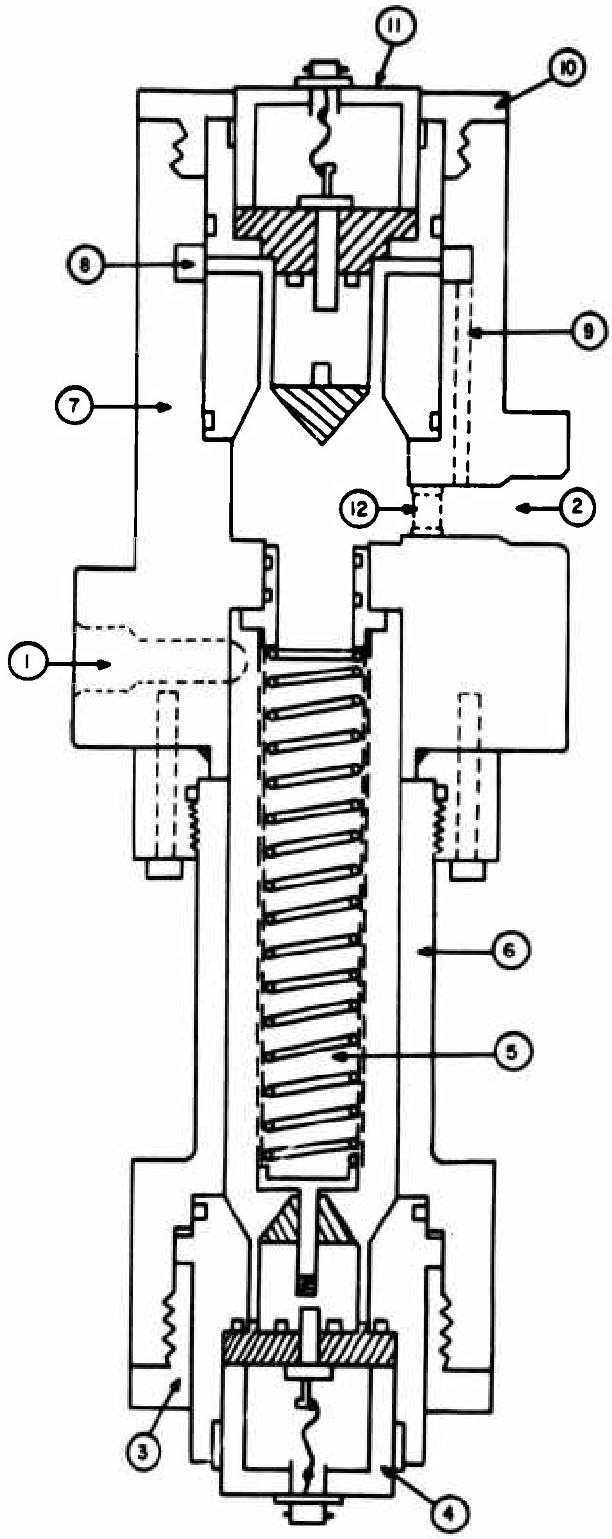

Figure 5. Sensor Assembly - Low Flow.

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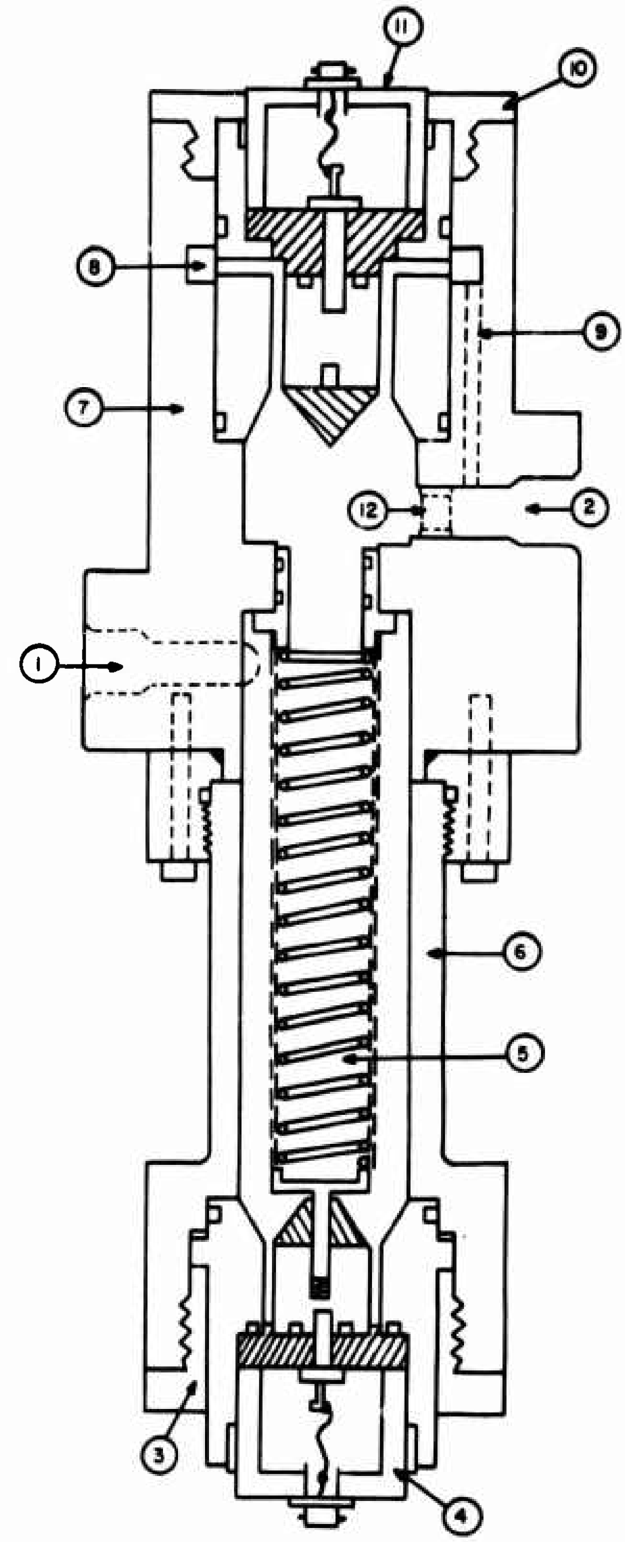

Figure 5. Sensor Assembly - Low Flow.

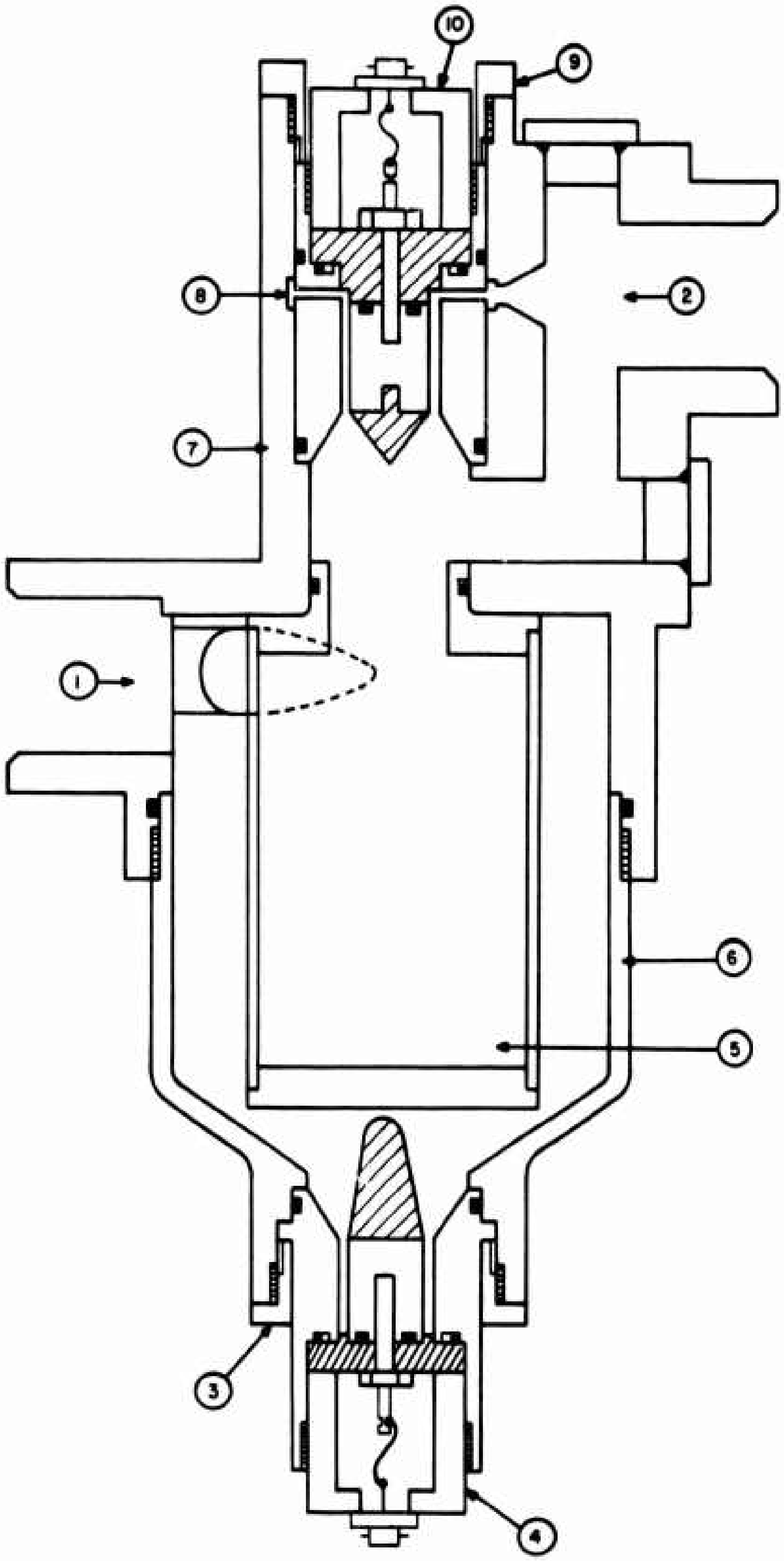

Figure 6. Sensor Assembly - High Flow.

allow for ease of bleeding oil. The parts as noted are:

1. Inlet Port
2. Outlet Port
3. Measurement Capacitor Retainer
4. Measurement Capacitor Assembly
5. 50-Micrometer Filter Screen
6. Sensor Body
7. Sensor Head
8. Collector Groove
9. Reference Capacitor Retainer
10. Reference Capacitor Assembly.

The numbers correspond to those in Figure 6.

CALIBRATION AND TEST

LOW-FLOW UNIT

Tests of the low-flow capacitative metallic debris monitor consisted of the following:

1. Pressure drop across the monitor.
2. Particle removal efficiency for iron filings in the size range of 40 to 300 micrometers at 1-gpm flow rate with MIL-L-7808E fluid.
3. Calibration of the accumulator meter in terms of scale reading as a function of weight of iron filings retained in the measuring capacitor.
4. Calibration of the difference meter in terms of the change in weight as a function of scale reading.

At 1-gpm flow, the pressure drop across the unit was less than 1 psi. The higher flow ranges for the unit cause increased pressure drop. At the highest practical flow of 5 gpm a pressure drop of 10 psi occurs.

Removal efficiency was determined by adding a known weight of iron filings to the flow stream upstream from the sensor assembly and subsequently measuring the quantity captured in the measuring capacitor. Table I shows the results of the test runs, conducted at 1-gpm flow rate. Efficiencies less than 100 percent indicate that particles of less than 50 micrometers pass through the screen.

TABLE I. PARTICLE REMOVAL EFFICIENCY

Low-Flow Sensor, 40-300 Micrometer Iron Filings

Wt. Added (mg)	Wt. Retained (mg)	Efficiency (%)
56.8	51.0	89.8
59.7	59.0	99.0
67.2	59.0	87.8
55.0	50.0	91.0
66.9	58.6	87.6
Mean Efficiency 91.04%		

Figure 7 shows the accumulator scale reading as a function of the weight of 40-300 micrometer size iron filings added to the measurement capacitor. One scale unit is equivalent to 1.4 milligrams collected. The region below 10 scale units is not reliable since the metal collected is not of sufficient height in the capacitor to cause changes in bridge unbalance. Scale unit refers to the integers of the scale from 0 to 100. A scale division refers the marked increments on the meter scale composed of either 2 or 5 scale units.

Table II shows the calibration for the difference meter. One scale unit difference on the accumulator meter is equivalent to 2.69 scale units on the difference meter. One scale unit on the difference meter is thus equivalent to a change of 0.52 milligram.

TABLE II. DIFFERENCE METER CALIBRATION

Low-Flow Sensor, 40-300 Micrometer Iron Filings

Actual Difference From Accumulator Meter	Difference Meter Reading	Ratio Difference Meter/Actual
9	24	2.66
20	56	2.80
15	42	2.80
19	50	2.63
16	45	2.82
16	43	2.69
24	61	2.55
19	53	2.79
35	85	2.43
Mean Ratio 2.69		

Since the smallest division on the accumulator meter is 2 scale units, each division is equivalent to 2.8 milligrams collected. The smallest division on the difference meter is 5 scale units, and each division on this represents a change of 2.6 milligrams.

HIGH-FLOW UNIT

Tests of the high-flow unit were the same as for the low-flow monitor.

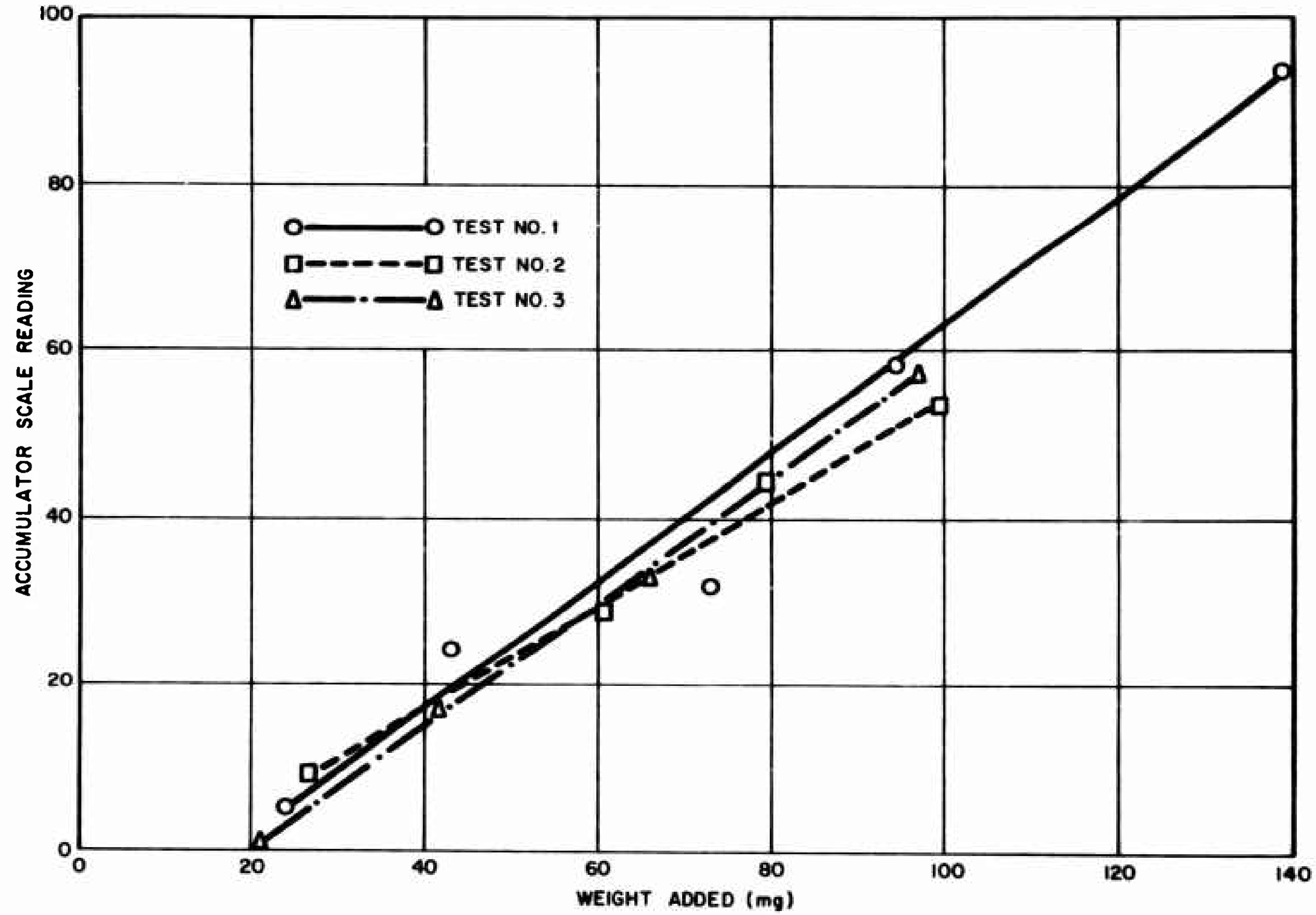

Figure 7. Accumulator Scale Reading vs. Weight of Iron Added.

Figure 8 shows the relationship between flow rate of MIL-L-7808E fluid and pressure drop across the monitor. At the expected 12 to 13 gpm flow for the UH-1 system, the pressure drop across the monitor would be less than 18 psi. Since the UH-1 lube oil pump develops pressures in excess of 100 psi with the pressure subsequently being regulated downward by more than 40 psi, the pressure drop across the monitor should cause no difficulty.

The results of removal efficiency for iron filings in the 40- to 300-micrometer size range is shown in Table III. Efficiencies less than 100 percent indicate that particles of less than 50 micrometers pass through the screen.

TABLE III. PARTICLE REMOVAL EFFICIENCY

High-Flow Sensor, 40-300 Micrometer Iron Filings		
Wt. Added (mg)	Wt. Retained (mg)	Efficiency (%)
146.8	135.0	92
130.7	117.0	89
145.6	131.0	90
151.4	139.0	92
113.3	100.8	89
Mean Efficiency = 90.4%		

Figure 9 shows the accumulator scale reading as a function of the weight of 40-300 micrometer size iron filings added to the measurement capacitor. One scale unit is equivalent to 6.25 milligrams collected in the capacitor. The region below 2 scale units is not reliable since the metal collected is not of sufficient height in the capacitor to cause measurable changes in bridge unbalance.

Table IV shows the calibration for the difference meter. One scale unit difference in accumulator meter reading is equivalent to 1.74 scale units on the difference meter. One scale unit on the difference meter is equivalent to 3.6 milligrams weight difference.

Since the smallest division on the accumulator meter is 2 scale units, each division is equivalent to 12.5 milligrams collected. The smallest division on the difference meter is 5 scale units, and each division represents a change of 18 milligrams.

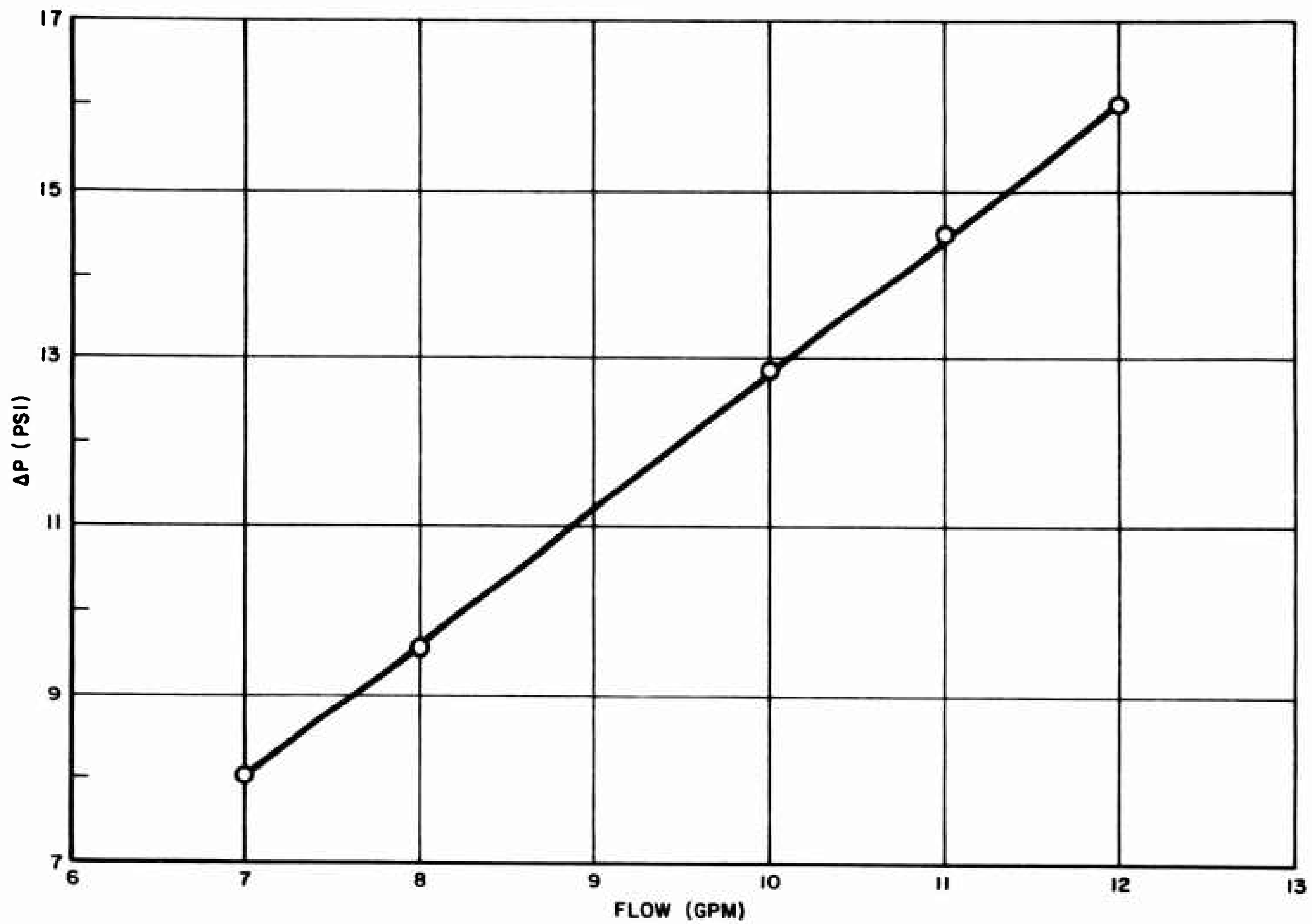

Figure 8. Flow of MIL-L-7808E Fluid vs. ΔP Across High Flow Monitor.

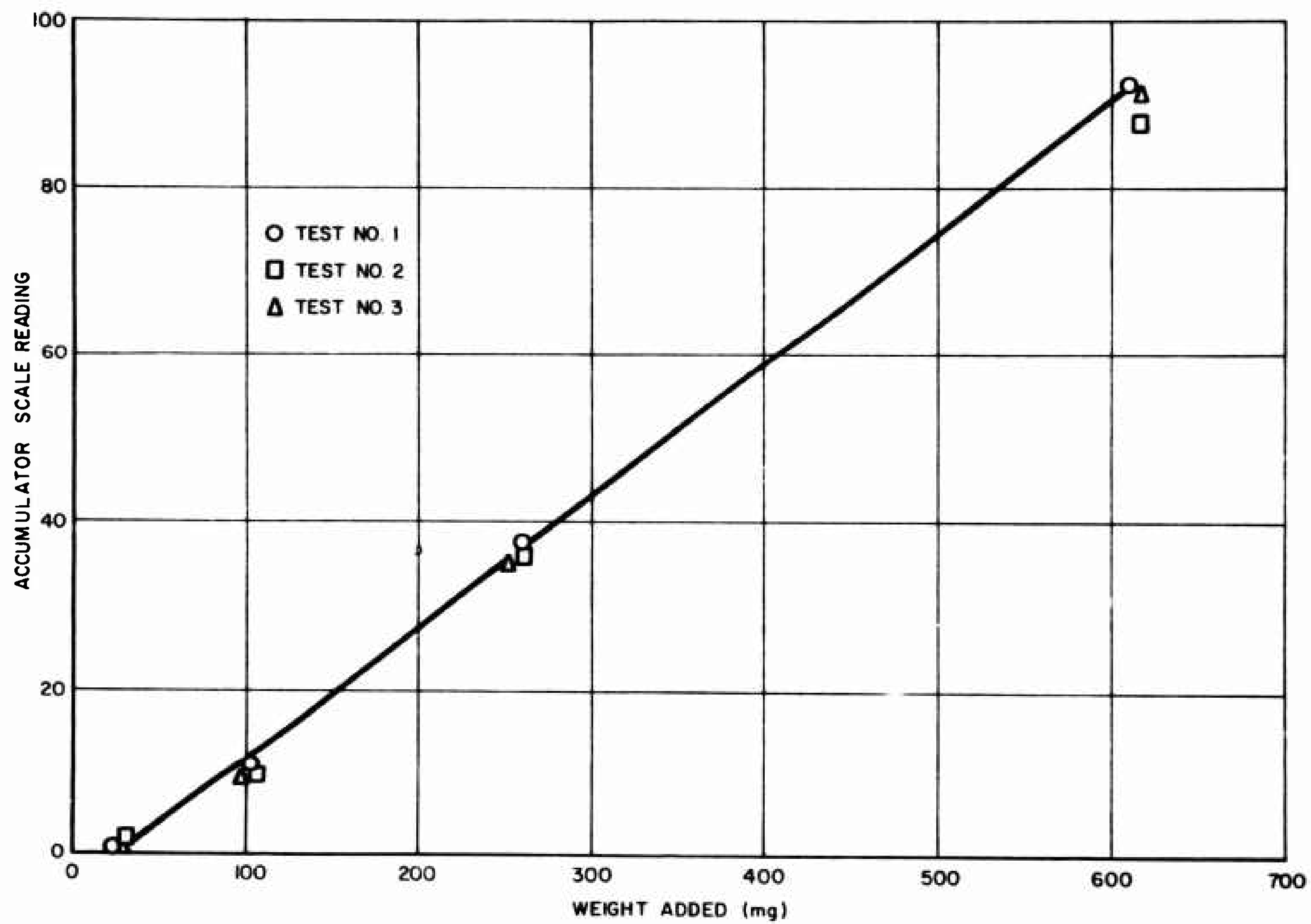

Figure 9. Accumulator Scale Reading vs. Weight of Iron Added.

TABLE IV. DIFFERENCE METER CALIBRATION

High-Flow Sensor, 40-300 Micrometer Iron Filings

Actual Difference From Accumulator Meter	Difference Meter Reading	Ratio Difference Meter/Actual
11	19	1.73
27	48	1.77
92	54	1.70
10	17	1.70
27	47	1.74
90	52	1.73
9	16	1.78
46	26	1.77
98	56	1.75
Mean Ratio = 1.74		

INSTALLATION AND OPERATION

LOW-FLOW UNIT

The low-flow monitor is designed for use with the UH-1 90-degree tail rotor gearbox. A pumping unit was required in order to test the monitor on the 90-degree gearbox system since the system does not normally use recirculated oil but relies on splash lubrication.

INSTALLATION

Monitor Cell

The monitor cell is to be installed in the oil lines *downstream* from the circulating pump and *upstream* from any system filters. Any other debris detectors which do not physically remove particles from the system should be mounted *upstream* from the cell, since the cell will remove particles from the system.

The cell inlet is lower than the outlet and is off center. The outlet is on center.

The cell should be mounted as near as possible to the circulating system low point in order to facilitate bleeding of air from the reference capacitor at the top of the cell.

Circulating Pump

A Gerotor circulating pump powered by a 115-Vac motor is provided. Two fittings are provided to connect the circulating oil system to the 90-degree gearbox. The fitting with 5/8-18 straight threads replaces the drain fitting in the gearbox and is to be connected to the pump inlet. The return line fitting replaces the oil filler cap on the gearbox. Oil lines may be hoses or the system may be tubed.

Readout Unit

The readout unit should be connected to the references and monitor capacitors in the cell with the two cables provided. The 90-degree connectors are normally attached at the cell, and the straight connectors are attached to the jacks on the face of the readout unit. The cables are matched for capacitance value, and any modification of the cable lengths should be made equally on both to preserve the match.

Power Supply

The power supply should be connected to the readout unit by means of the cable provided. Before plugging in the 115 Vac cord for the power supply unit, refer to the following section on "Operation." A switch for the timer for automatic operation is provided. This switch should be "Off" during the check operation.

OPERATION

Monitor Cell - Fill and Bleed

Start oil circulating system to provide pressure for filling and bleeding the monitor cell with lube oil. Bleed the cell by loosening the brass cap nut on the side of the cell. Stop circulation and tap the cell lightly to dislodge air from the monitor capacitor at the cell bottom, and repeat the fill and bleed procedure.

Readout Unit

With the readout unit connected to the cell, place the range selector switch to "Low Range". This prevents overloading of the meters in subsequent operations. Three output terminals are provided on the rear of the unit. The black terminal is the unit ground. The red terminals are the signals that drive the panel meters and their bleeder resistors. They can vary from -15 to +15 volts and are proportional to the meter readings. The outputs are relatively low impedance and can be used to drive most high-input-impedance recorders directly. In using a recorder with the capacitative debris monitor, it must be remembered that signal levels do not change continuously but only at the sampling interval. The sampling interval is 2 hours with automatic operation. Sampling may be performed at any other time by depressing the manual update switch for approximately 1 minute.

Power Supply

Connect the power supply to a 115 Vac source and move the operating switch to the "On" position.

Check Operation

With power on, depress the manual update switch on the readout unit and hold for 1 minute. The meters may not read zero at this time; if not, the operation should be repeated. After the second cycling, both the accumulator meter and the difference meter should read zero. Failure of the meters to read zero indicates a bridge unbalance, which could result from improper connections to the sampling cell or air in either the monitor or the reference

capacitor. After the condition is corrected, repeat the manual update procedure to obtain a zero reading.

When a zero reading has been obtained, move the range selector switch to "Operate". Recheck the zero reading as before. A slight shift from zero may be observed on the accumulator meter and may be ignored. With the unit zeroed, timer switch "On", and the range selector switch on "Operate", sampling is automatic at 2-hour intervals. Automatic sampling can be disabled by turning the timer switch to "Off".

The above procedure for obtaining zero readings of the meters is designed to insure that no gross unbalance exists in the sensing unit. If either meter has a small deviation from zero after the above procedure, it will not interfere with proper operation of the unit. The parameters of concern are the change of the readings with sampling.

CLEANING

After a period of operation, the accumulated debris in the monitor capacitor must be removed to keep the range of the meter from being exceeded. With all power off, remove the monitor capacitor from the cell. Rinse as much of the debris as possible from the capacitor using "Freon" cleaning solvent in a squeeze-type plastic wash bottle. Care must be exercised to avoid scratching the polytetrafluoroethylene coating on the inner capacitor plate. After rinsing the capacitor, place it on its side for approximately 1 minute in an ultrasonic cleaner with "Freon" solvent. Place the capacitor open end down and continue cleaning for 20 minutes. Replace the capacitor in the cell, and follow the procedures outlined under "Operation".

HIGH-FLOW UNIT

INSTALLATION

The high-flow monitor is designed for use in tests on the UH-1 main gearbox. The oil scavenge pump in this system circulates oil at a rate of 12-13 gpm at normal rpm. Since the circulating pump and primary filters are enclosed in the gearbox and since oil flow lines are internally manifolded, the high-flow sensor can be mounted only at the point where the oil line emerges from the transmission. The mounting location is shown in Figure 10. The internal disc type filter must be removed upstream from the monitor to keep from removing metal particles which will be captured in the monitor cell. The second, downstream filter should be retained to remove particulates smaller than 50 micrometers which may pass the monitor cell.

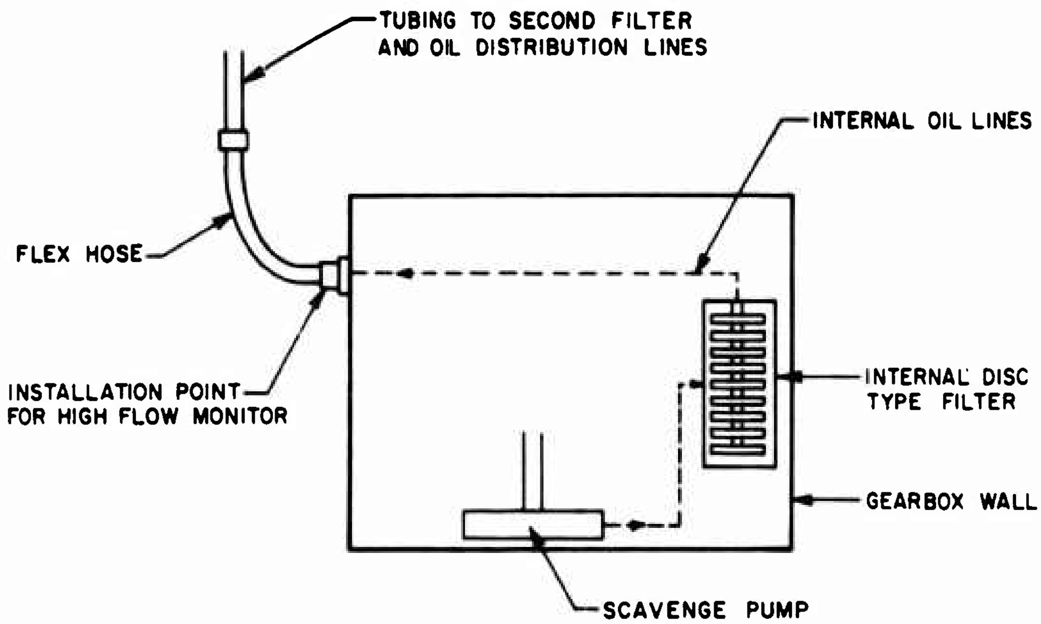

Figure 10. High-Flow Monitor Mounting Location on UH-1 Main Gearbox.

OPERATION

The readout unit should be connected to the reference and monitor capacitors with the two cables provided. The 90-degree connectors are normally attached at the cell, and the straight connectors are attached to the jacks on the face of the readout unit. The cables are matched for capacitance value, and any modification of the cable lengths should be made equally to preserve the match. With the monitor mounted at the point shown in Figure 10, and with oil circulating, bleed the air from the monitor at the top plug.

Connect the readout unit to a 115-Vac, 60-Hz power source and move the operating switch to the "On" position.

With the power on, depress the manual update switch on the readout unit and hold for 1 minute. The meters may not read zero at this time; if not, the operation should be repeated. After the second cycling, both the accumulator meter and the difference meter should read zero. Failure of the meters to read zero indicates a bridge unbalance, which could result from improper connections to the sampling cell or air in either the monitor or the reference capacitor. After the condition is corrected, repeat the manual update procedure to obtain a zero reading.

A slight shift from zero may be observed on the accumulator meter and may be ignored. With the unit zeroed, turn the timer switch "On". Sampling is automatic at 2-hour intervals. Automatic sampling can be disabled by turning the timer switch to "Off".

The above procedure for obtaining zero readings of the meters is designed to insure that no gross unbalance exists in the sensing unit. If either meter has a small deviation from zero after the above procedure, it will not interfere with proper operation of the unit. The parameter of concern is the change of the readings with sampling.

Two sets of output jacks are provided at the back of the readout unit for connection to any high-input-impedance recorder. Accumulator meter and difference meter values may be recorded using these connections.

CLEANING

After a period of operation, the accumulated debris in the monitor capacitor must be removed to keep the range of the meter from being exceeded. With all power off, remove the monitor capacitor from the cell. Rinse as much of the debris as possible from the capacitor using "Freon" cleaning solvent in a squeeze-type plastic

wash bottle. Care must be exercised to avoid scratching the polytetrafluoroethylene coating on the inner capacitor plate. After rinsing the capacitor, place it on its side for approximately 1 minute in an ultrasonic cleaner with "Freon" solvent. Place the capacitor open end down and continue cleaning for 20 minutes. Replace the capacitor in the cell, and follow the procedures outlined in "Operation".

CONCLUSIONS

1. The low- and high-flow units are satisfactory for tests with the UH-1 90-degree and main gearboxes respectively. Normal sampling intervals of 2 hours are established to correspond to an expected metal pickup corresponding to one accumulator meter division per sampling interval.

2. The units should be tested on the systems of the UH-1 series aircraft.